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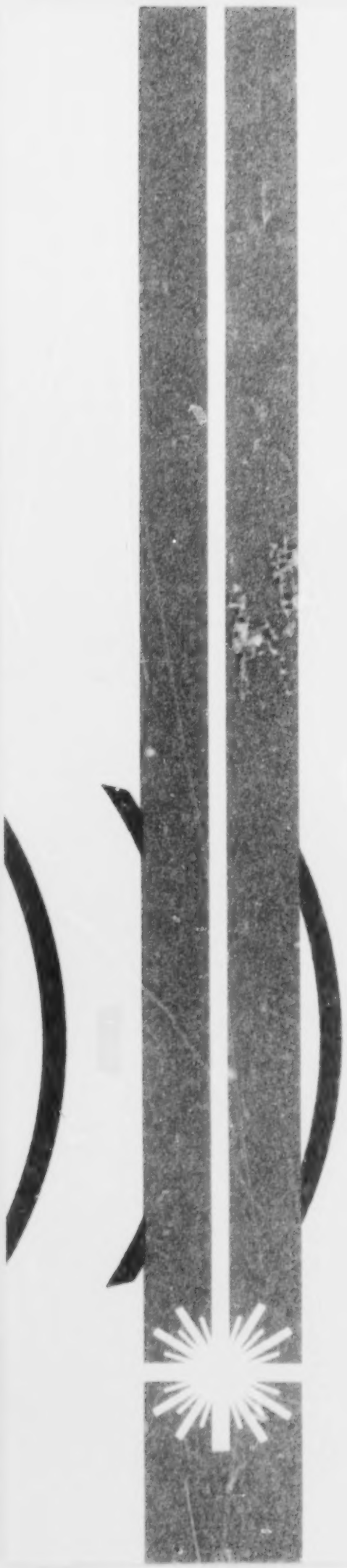

X-RAY EMISSION FROM COLD-CATHODE GAS DISCHARGE TUBES USED FOR EDUCATIONAL PURPOSES

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William S. Properzio, Ray C. Woodcock,
and Sidney D. Heidersdorf

X-ray Exposure Control Laboratory
Division of Electronic Products

February 1970

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
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FOREWORD

The Bureau of Radiological Health, formerly the National Center for Radiological Health, continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and non-ionizing radiation.

Within the Bureau, the Division of Electronic Products (1) develops and administers performance standards for radiation emissions from electronic products, (2) studies and evaluates emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conducts or supports research, training, development and inspections to control and minimize such hazards, and (4) tests and evaluates the effectiveness of procedures and techniques for minimizing such exposures.

The Bureau publishes its findings in Radiological Health Data and Reports (a monthly publication), the Environmental Health Series, Public Health Service numbered reports, appropriate scientific journals, and Division technical reports.

The technical reports of the Division of Electronic Products (DEP) allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

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John C. Villforth
Bureau Director

PREFACE

The National Council on Radiation Protection and Measurements (NCRP) has made recommendations regarding radiation protection in educational institutions in Report #32. The report identifies gas discharge tubes in general as potertial sources of X-rays and specifically mentions cold-cathode X-ray tubes in this regard. However, the report does not specifically identify gas discharge tubes that may emit X-rays incidental to their intended use. This report describes a study undertaken by the X-ray Exposure Control Laboratory to identify those cold-cathode gas discharge devices used in educational institutions that may emit X-radiation. The tubes were operated from various commercially available high voltage sources suggested by the manufacturer and typical of those used in high schools; for those found to produce X-rays, radiation measurements were made. In addition to cold-cathode X-ray tubes, a number of other gas discharge devices were found to emit X-rays.

The information contained in this report has been used as supporting material for the development of performance standards for cold-cathode gas discharge devices used for educational purposes under the authority of the Radiation Control for Health and Safety Act of 1968 (Public Law 90-602).

The Environmental Health Service, in the meantime, has taken action to stop the sale of devices identified in this report as producing X-radiation incidental to their intended use until they are designed to comply with the new performance standards.

Robert L. Elder, Sc.D.
Acting Director
Division of Electronic Products

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X-RAY EMISSION FROM COLD-CATHODE GAS DISCHARGE TUBES USED FOR EDUCATIONAL PURPOSES

William S. Properzio, Ray C. Woodcock,
and Sidney D. Heidersdorf[1]

1. INTRODUCTION

Many schools use radiation-producing equipment in their science class demonstrations. The importance of an awareness of radiation hazards and good radiation protection techniques related to the use of such equipment cannot be overstated. National and international radiation protection organizations emphasize the desirability of keeping radiation exposure to younger age groups as low as possible. The teachers who use the radiation-producing equipment should therefore understand the radiation hazards and should know and practice good radiation protection techniques in the classroom so that exposure to themselves and their students will be kept to a minimum.

Recognizing the possible health implications of using radiation-producing devices in schools, the American Association of Physics Teachers requested the National Council on Radiation Protection and Measurements (NCRP) to provide suitable information on radiation protection. After the NCRP had conducted a questionnaire survey of science teachers, the Division of Radiological Health (now the Bureau of Radiological Health) in 1962 conducted a survey in four schools. An evaluation of the data by a scientific committee appointed by the NCRP concluded that there was a potential problem worthy of NCRP consideration. As a result, the NCRP issued Report #32, "Radiation Protection in Educational Institutions." In this report, the NCRP recommended maximum permissible doses for students 18 years of age or less while conducting educational activities. The report identifies gas discharge tubes in general as potential sources of X-rays and specifically mentions cold-cathode X-ray tubes in this regard. However, the report does not specifically identify gas discharge tubes that may emit X-rays incidental to their intended use.

In addition to NCRP efforts, a number of State radiological health agencies and individuals have attempted to identify devices

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that are capable of producing X-rays and to evaluate the potential radiation exposure to students. Radiation measurements were usually made under field conditions. While the results were certainly adequate for the intended purpose of identifying devices capable of producing X-rays, a complete evaluation of the operating and output characteristics of the devices requires conditions of space and equipment which only a laboratory can provide. In addition, field surveys are necessarily limited to the observation of only one or two types of tubes under constant conditions. As a consequence, the information available is a compilation of random observations made under various conditions by different individuals using different techniques.

To provide specific information about the various gas discharge tubes, the X-ray Exposure Control Laboratory undertook a study to identify specific gas discharge devices that emitted X-radiation and to evaluate the X-ray output under controlled conditions of operation. A variety of commercially available cold-cathode gas discharge tubes were obtained and tested. The tubes were operated from various commercially available high voltage sources suggested by the tube manufacturer. The objectives of the study were as follows:

1. To investigate X-ray emission from cold-cathode gas discharge X-ray tubes.
2. To identify those tubes which emit X-rays incidental to their intended use.
3. To measure X-ray exposure levels.
4. To define or map the radiation patterns about such devices.
5. To identify operating characteristics.
6. To determine factors which influence X-ray production in cold-cathode gas discharge tubes.
7. To formulate recommendations for operation of these devices.

This report presents the experimental results obtained by the X-ray Exposure Control Laboratory with regard to X-ray output from cold-cathode gas discharge X-ray tubes and other gas discharge tubes, some of which were found to emit X-rays incidental to their intended use. Based on these results, specific recommendations are directed to the science teacher utilizing the equipment, to distributors selling the equipment, and to State or local radiological health agencies.

2. COLD-CATHODE GAS DISCHARGE TUBES

Gas discharge devices first came into use in the latter half of the nineteenth century. Physical scientists of that time studied the various discharge phenomena in their attempts to study the structure and properties of matter. Today the major application of these tubes is the demonstration of physical phenomena in educational institutions.

X-ray tubes can be broadly subdivided into two groups, gas tubes and vacuum (or Coolidge) tubes. In the gas tubes, electrons are liberated from the cold-cathode surface by positive ion bombardment. These positive ions are generated by ionization of gas atoms contained in the tube. In the Coolidge tube, a high vacuum is obtained and the bombarding electrons are released from a heated filament by thermionic emission.

2.1 Historical Background

William Conrad Roentgen made his discovery of X-rays while experimenting with a Crookes cold-cathode tube (fig. 1). Electrons are emitted from the cathode in a direction perpendicular to its surface. Collision interactions between the electrons and contained gas atoms take place but the mean free path for the electrons is such that a majority will traverse the tube and arrive at the glass walls opposite the cathode with sufficient energy to produce X-rays upon collision.

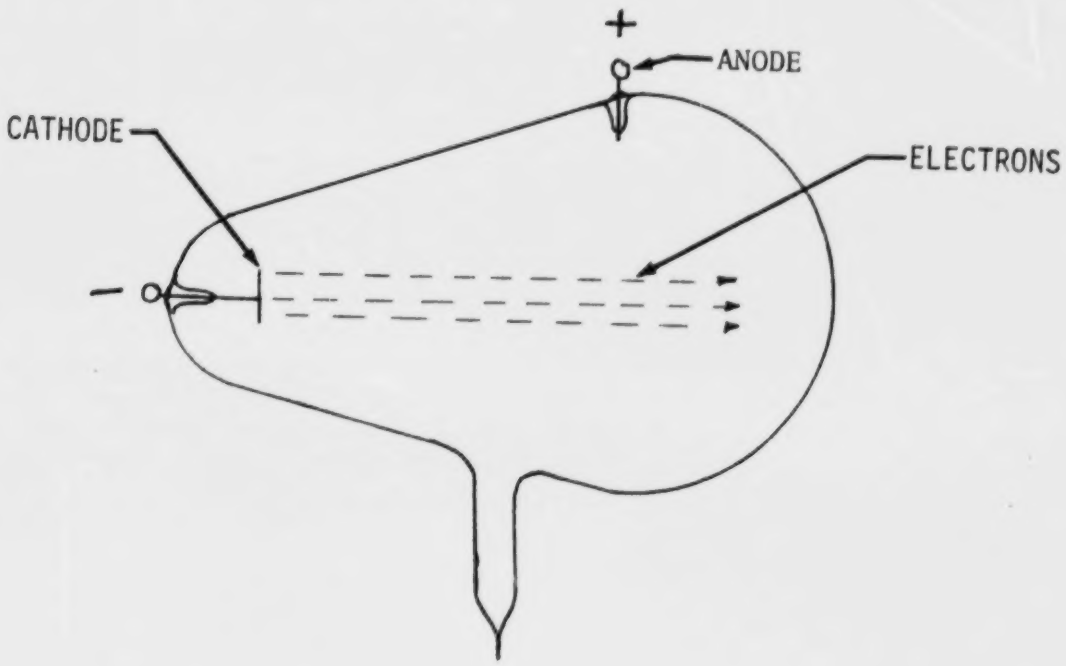

Figure 1. Crookes cold-cathode gas discharge X-ray tube

Following Roentgen's discovery, improvements in the design of gas tubes were quickly introduced. Campbell-Swinton introduced a platinum foil target and Jackson reduced the focal spot size by use of a concave cathode that would focus the electrons to a small spot on the anode (1). Another significant improvement was the placement of the target material in a large heat sink so that longer tube operation could be obtained than from the thin foil target tubes.

The time and frequency of use of cold-cathode tubes would cause variations of internal gas pressure of these gas tubes. When a tube was operated, two opposing reactions occurred that affected this gas pressure. An electrical pumping or getter action took place, removing gas atoms and thus increasing the internal vacuum, while an outgassing from internal tube parts tended to decrease the vacuum. To help attain the correct gas pressure, various gas regulating devices were incorporated into the tubes. They usually consisted of an auxiliary chamber containing some material or device from which gas could be liberated. Operation of these regulating devices was usually controlled by external heating or through an electrical discharge.

Coolidge pointed out that the useful life of a gas tube is limited by the permanent "electrical clean-up" of gas in the device (1). He stated that gas released from the cathode was of particular importance for proper operation. If a tube had been operated for a length of time sufficient to completely outgas the cathode, gas from the regulator could no longer compensate for the getter or gas removal action and upon further operation of the tube immediate "clean-up" would occur.

When this condition was reached, proper operation could only be obtained by rebuilding the tube. This rebuilding procedure would involve the placement of a new hydrogen-rich aluminum cathode. The fact that, following this procedure, a tube would again operate normally points to the effect of gas liberation from the hydrogen-rich cathode as necessary for proper operation. This effect was well recognized by the manufacturers of gas tubes who carefully refrained from operating them any longer than necessary while connected to the pump during manufacture.

The foregoing discussion points out some of the problems associated with proper operation of a cold-cathode gas discharge X-ray tube. Attempts to produce more reliable tubes led to the development of the hot-cathode high vacuum, Coolidge tube which is in almost universal use today. Educational uses remain as one of the few applications where cold-cathode gas discharge X-ray tubes are now utilized. The major reason for their continued use in this area is the fact that they are relatively inexpensive and require a minimum amount of auxiliary equipment to operate. X-ray tubes using the principle of field emission can also be classified as cold-cathode tubes but operate under high vacuum conditions and will not be included in this study.

The cold-cathode gas discharge X-ray tubes currently sold by a number of scientific supply houses in this country are of the so-called "Muller" type (fig. 2) (2). Tubes of this type can be purchased for about fifty dollars. A variety of high voltage sources may be used to operate these devices; however, induction coils are the most popular. These coils can be either homemade or purchased from the same suppliers as the tubes. These commercial induction coils, depending on their voltage rating, typically range in cost from ten to one hundred and fifty dollars.

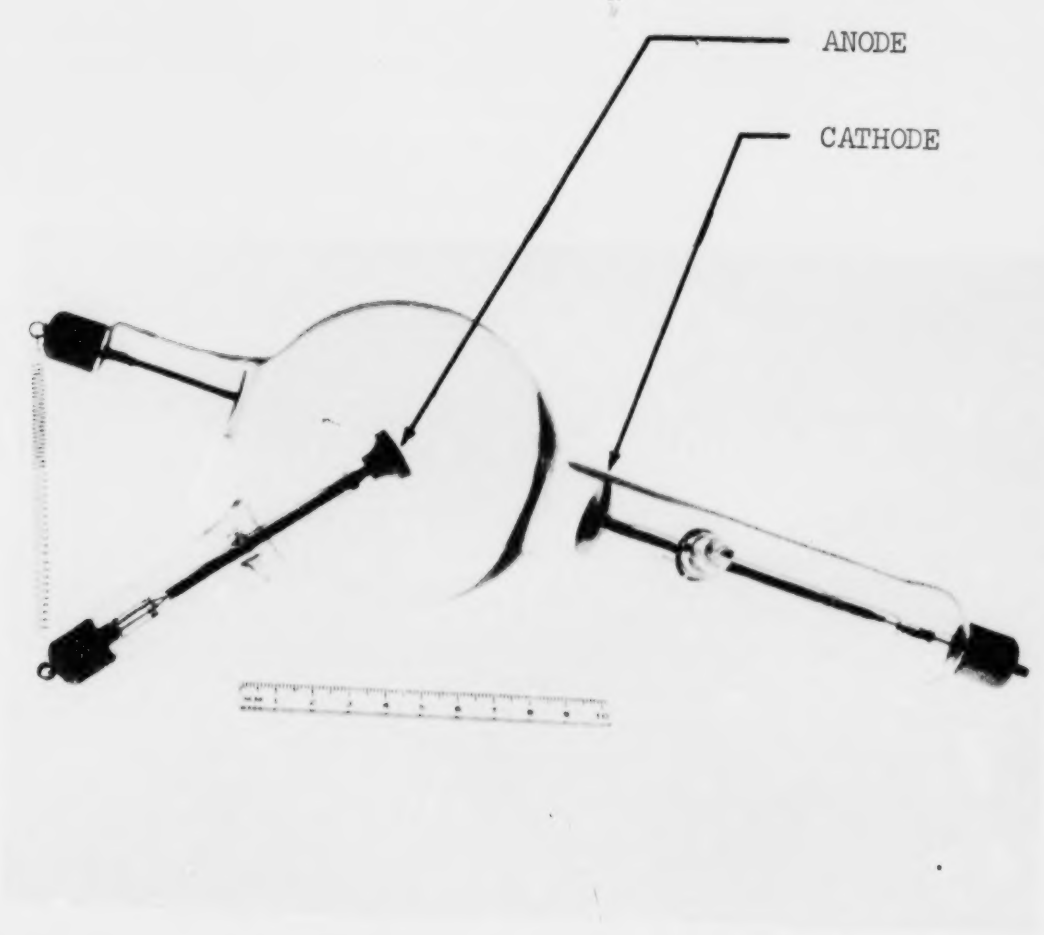

Figure 2. Muller type cold-cathode gas discharge X-ray tube

2.2 Experimental Procedures

Measurements of radiation output from three cold-cathode gas discharge X-ray tubes and numerous other gas discharge tubes were made. These tubes were operated successively from a hand-held Tesla coil, and two induction coils; one advertised as capable of producing a 3-inch spark and the other a 6-inch spark.

The dosimeters used in this study were LiF TLD-100 extruded rods measuring approximately 6 mm x 1 mm. TL dosimeters were used because their size makes possible good point measurements in a radiation field and many such measurements can be made with a single exposure. The TLD reader was an Eberline Model TLR-5. LiF was used because its energy response does not vary greatly at the low energies encountered in the study. Typical energy response curves for LiF show it to vary less than 15 percent over the energy range of 20 to 70 keV which includes the region of interest for our measurements (3). Consequently, errors in the selection of calibration energies would not significantly affect the results.

Calibrations were made with a G.E. Maximar 100 X-ray machine using calibrated Victoreen condenser R-meters to monitor the exposures. The kVp of the calibration machine was selected to match the operating voltage of the cold-cathode gas discharge X-ray tube estimated by a parallel spark-gap measurement. One millimeter of aluminum filtration was used and considered a reasonable approximation of the inherent filtration of gas discharge tubes.

A cutout was made for the X-ray tube in a piece of cardboard-backed paper, as shown in figure 3. The dosimeters were placed in gelatin capsules and located along radials from the target anode. Measurements were made at 3, 6, 9, and 12 inches from the anode as well as at the surface of the tube in the hemisphere opposite the target. Measurements were also made with the tube rotated 90° about the target anode axis from the position shown in figure 3. After a 5-minute exposure, the dosimeters were removed and read. The appropriate calibration factors were applied to the readings to give the results as Roentgens per hour (R/hr).

2.3 Experimental Observations

2.3.1 Cold-Cathode Gas Discharge X-ray Tubes

Three tubes of this type were tested. It was found that these tubes will produce X-rays when operated with a forward or reverse potential. Under reverse potential, measured outputs were observed to drop by a factor of 50 to 100. Iso-exposure contours for the three tubes were similar in shape but varied in value, depending on the particular tube and high voltage source used.

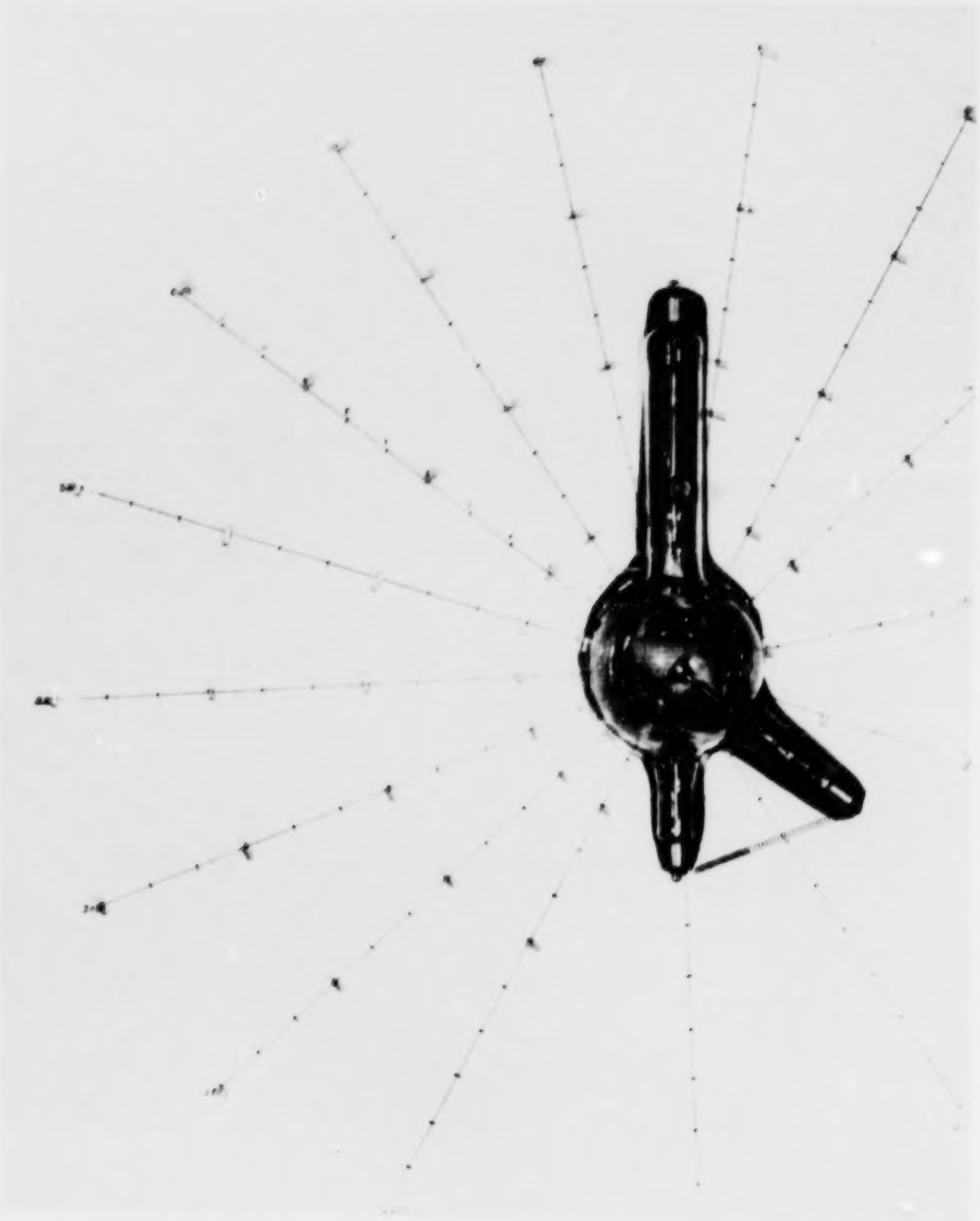

Figure 3. Placement of dosimeters for radiation measurements; radials are marked in one-inch divisions

Figures 4 to 6 are complete iso-exposure patterns for tube #2 (the tube with greatest output), showing the output with both the forward and reverse potential applied using an induction coil capable of a 3-inch spark.

Table 1 is a listing of exposure levels measured from three tubes operated from different high voltage sources. Readings are shown in the region of maximum exposure. As shown in figure 7, radial A is a line perpendicular to the anode surface, radial C is a line perpendicular to the tube axis and radial B bisects A and C. With the hand-held Tesla coil an exposure rate for reverse potential only is given. The output of the coil, about 25 kV, was not sufficient to cause the tube to conduct in the forward direction. Table 2 gives the approximate operating conditions of the three tubes. The kV was estimated by a parallel spark-gap method (see appendix A) and the mA determined by placing a d-c milliammeter, 1 mA full scale, in series with the high voltage supply.

Table 1. Measured exposure rates from three cold-cathode gas discharge X-ray tubes operated from various high voltage sources

Tube (High Voltage Source)	Exposure Rate in R/hr at 1 foot from anode		
	Radial A	Radial B	Radial C
Tube #1			
*3" max. spark gap induction coil	9.7	10.4	6.7
*6" max. spark gap induction coil	53.9	54.8	42.4
Tube #2			
*3" max. spark gap induction coil	72	75.5	68
*6" max. spark gap induction coil	208	217	178
Hand-held Tesla coil (tube operated under reverse potential)	0.5	0.49	0.63
Tube #3			
*3" max. spark gap induction coil	13.2	15	13.3
*6" max. spark gap induction coil	94.4	87	96.2

*Maximum spark gap designations are those claimed by the manufacturers and are cited here for identification purposes only.

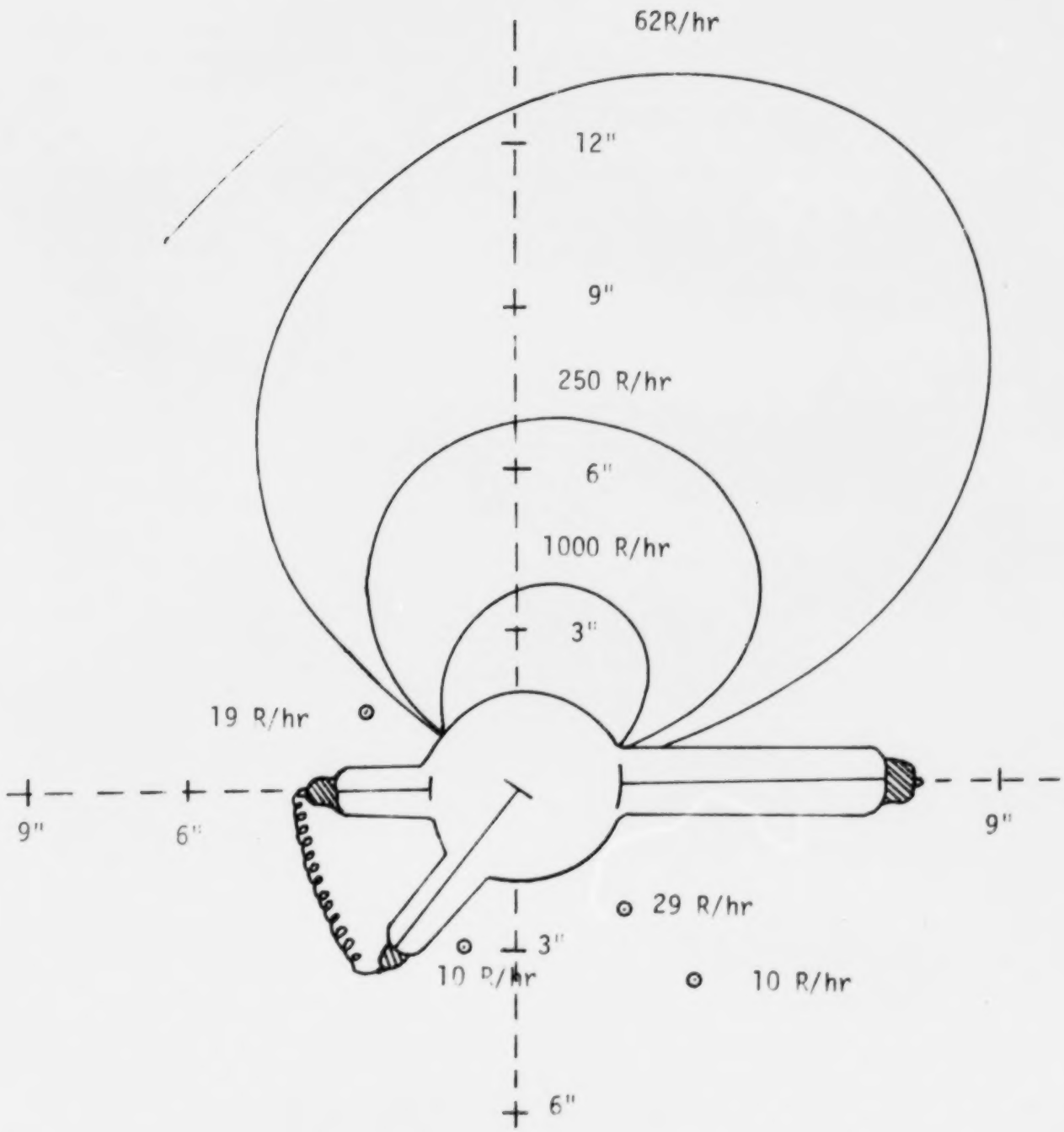

Figure 4. X-ray output: tube #2 with small induction coil

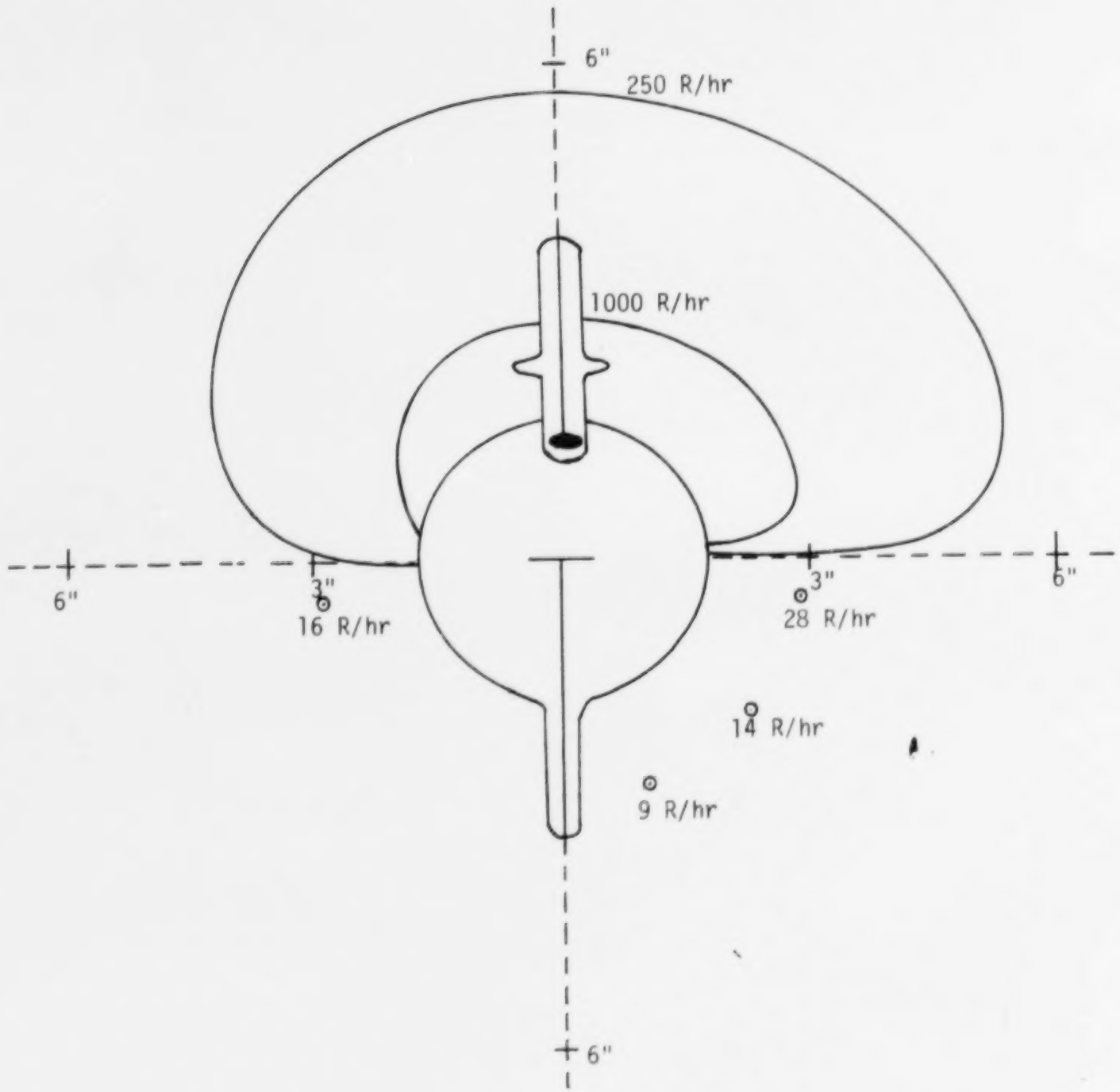

Figure 5. X-ray output; tube #2 rotated 90° on anode axis, with small induction coil

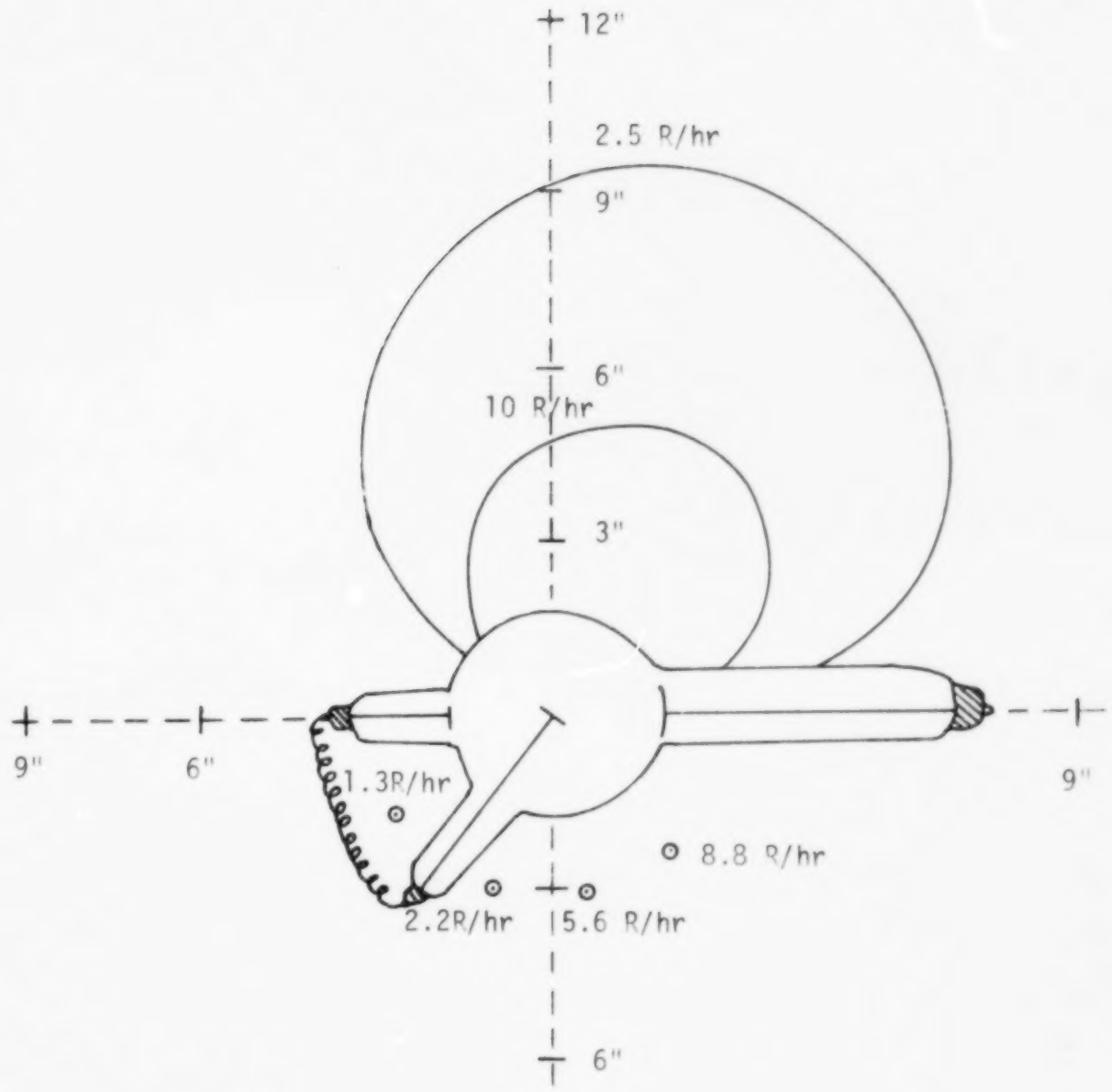

Figure 6. X-ray output; tube #2 with small induction coil, reverse potential

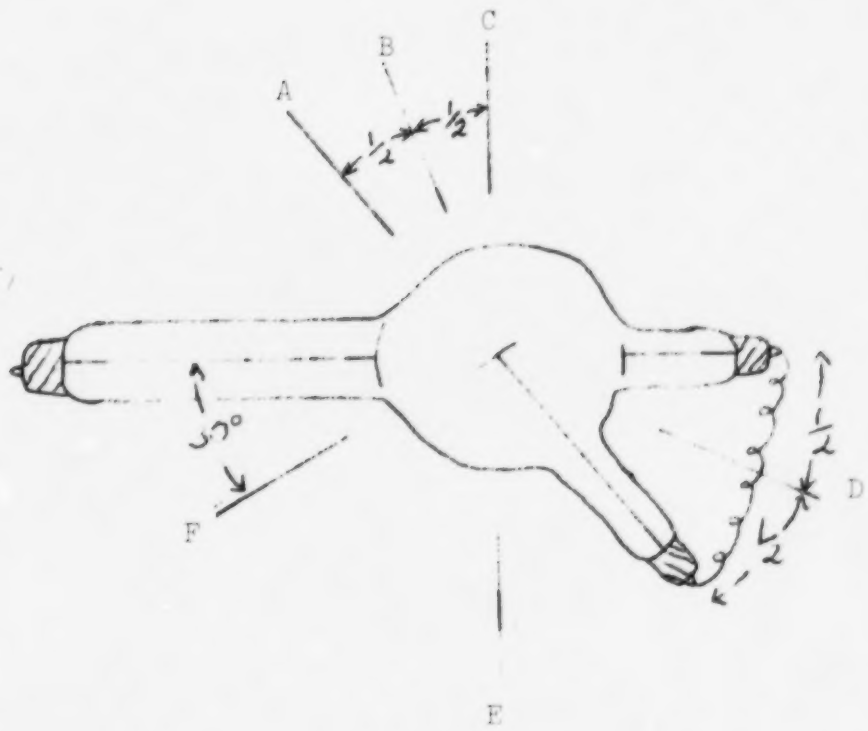

Figure 7. Cold-cathode gas discharge X-ray tube showing radial locations for exposure measurements

Table 2. Observed electrical characteristics of three cold-cathode gas discharge X-ray tubes

Source	Primary Volts	Tube #1		Tube #2		Tube #3	
		kVp	mA	kVp	mA	kVp	mA
Tesla Coil	-	25	.01	25	.09	-	-
Small (3-inch) Induction Coil	6 (d-c)	65	.03	50	.18	65	.10
Large (6-inch) Induction Coil	10 (d-c)	75	.15	73	.20	85	.15

A study using tube #2 and the large (6-inch) induction coil was made to determine exposure levels at various distances from the tube along the radials diagrammed in figure 7. Dosimeters were placed at distances of 1-, 2-, 4-, 8-, and 16-feet from the target. A 10-minute exposure was made and the exposure rate found at each point. The results are given in table 3. Note that the values presented here are not in exact agreement with those presented in table 1 for tube #2. This variation in output from day to day has been reported to be a characteristic of gas discharge tubes.

Table 3. Measured exposure rates in R/hr at various distances from a cold-cathode gas discharge X-ray tube

Radial	Distance from Anode Surface (tube #2)				
	1 ft.	2 ft.	4 ft.	8 ft.	16 ft.
A	240	56.1	12.6	2.89	0.530
B	281	64.8	15.8	3.45	0.773
C	241	55.1	13.6	2.42	0.598
D	2.84	0.902	0.209	-	-
E	5.45	1.47	0.384	-	-
F	133	33.5	6.78	-	-

2.3.2 Cold-Cathode Gas Discharge Tubes (not intended to produce X-rays)

X-rays were not detected from the following tubes while operating from an induction coil capable of producing a 6-inch spark:

a. Vacuum Discharge Tube (connected to laboratory mechanical vacuum pump) (figure 8)
b. High and Low Vacuum Effect Tube (figure 9)
c. Goldstein Canal Ray Tube (figure 10)
d. Geissler Tube (figure 11)
e. De la Rive Discharge Tube (figure 12)
f. Kinetic Effects Tube (figure 13)

Tubes found by our investigation to produce X-rays incidental to their intended use were:

a. Heat Effect Tube (figure 14)
b. Magnetic Effect Tube (figure 15)
c. Fluorescence Effect Tube, also known as a Shadow Effect or Maltese Cross Tube (figure 16)

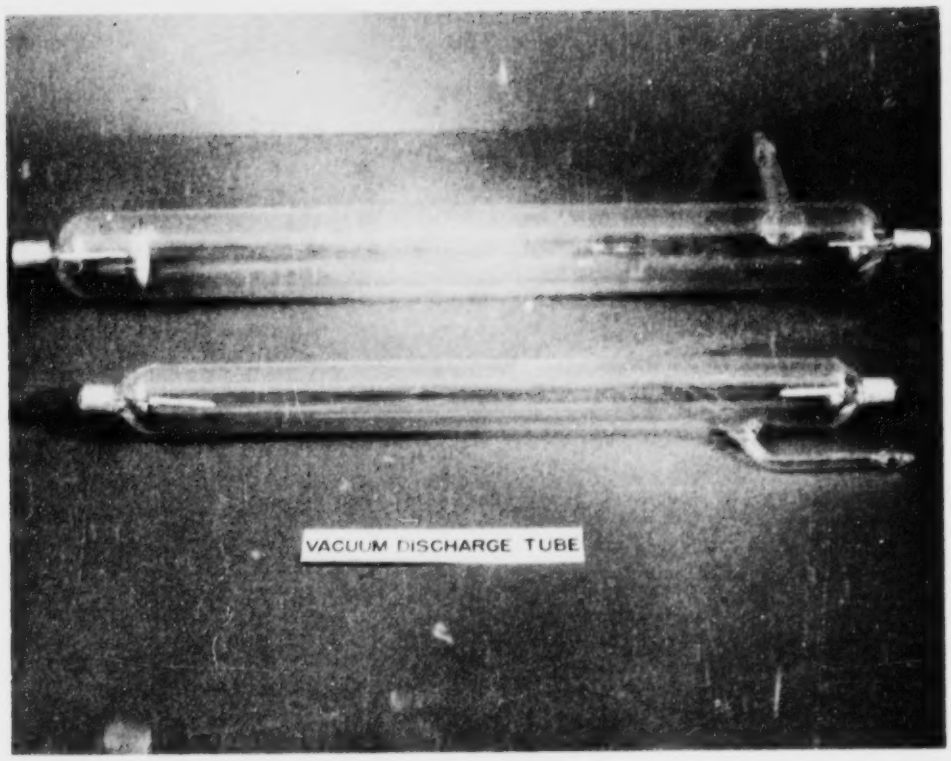

Figure 8. Vacuum discharge tube

Figure 9. High or low vacuum effect tube

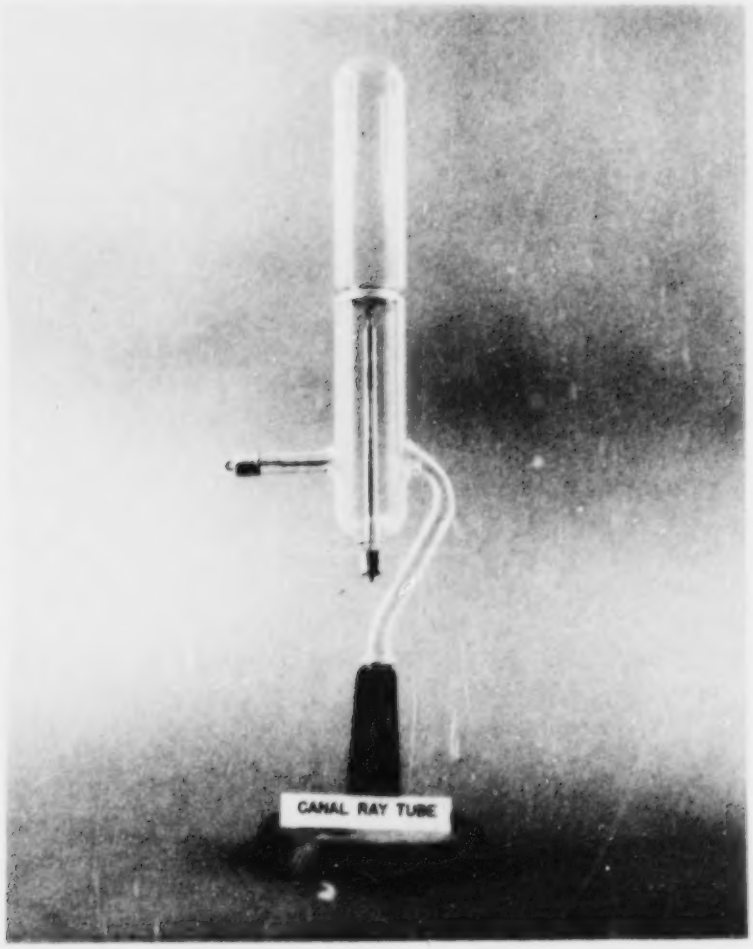

Figure 10. Goldstein canal ray tube

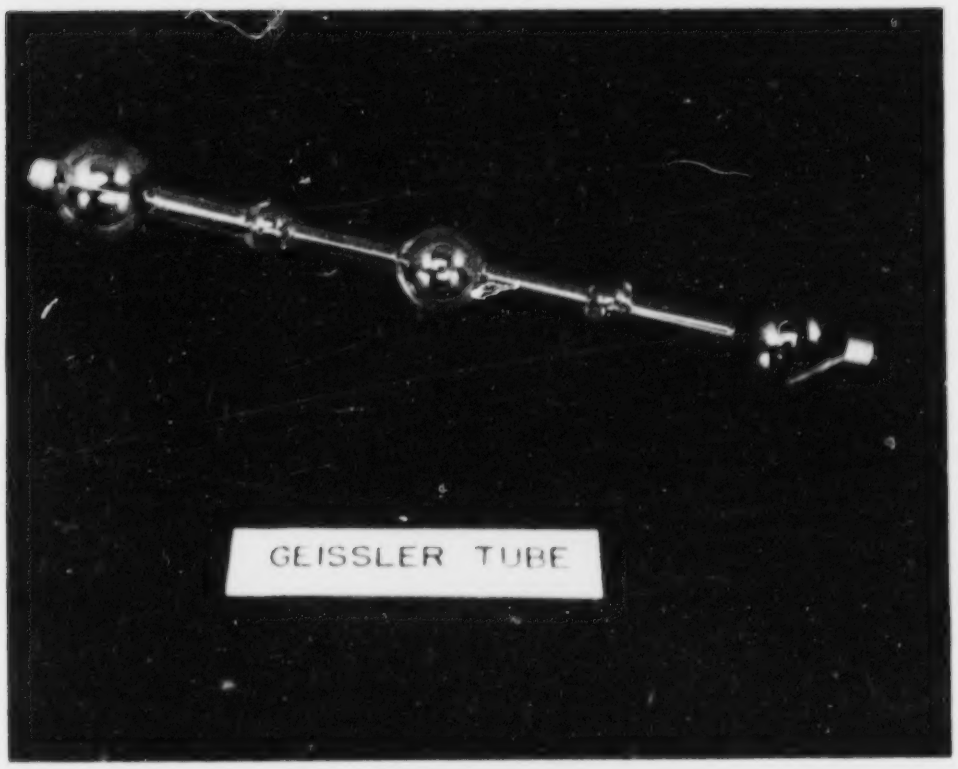

Figure 11. Geissler tube

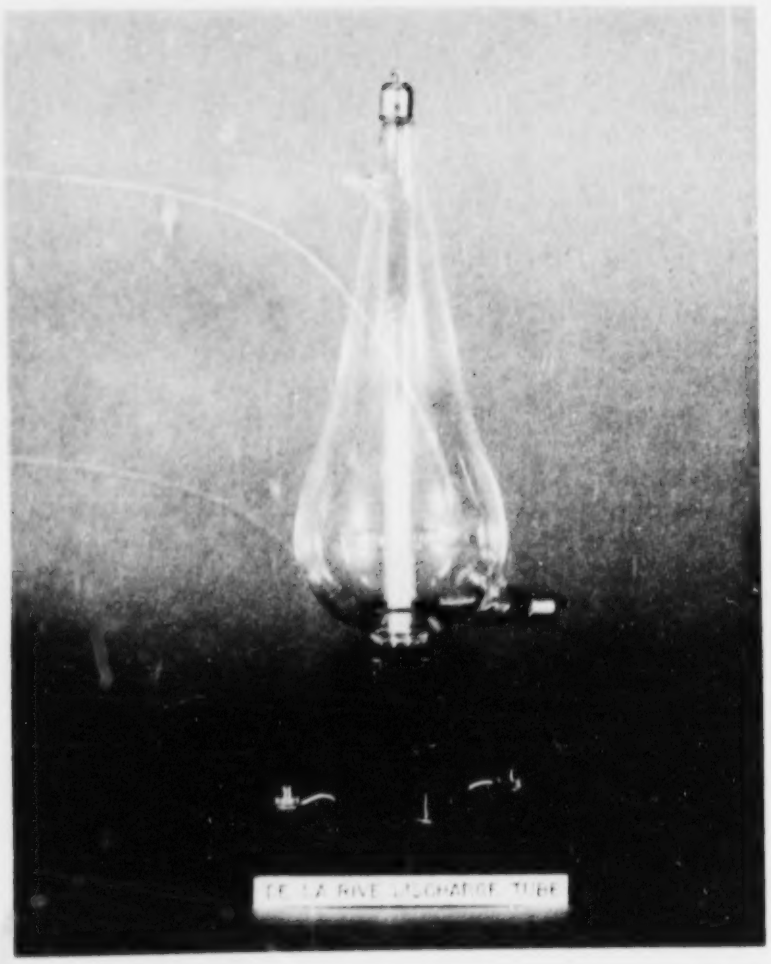

Figure 12. De la Rive discharge tube

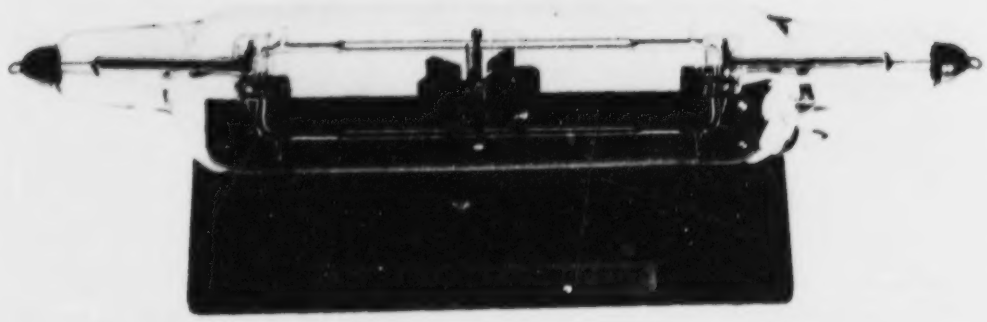

Figure 13. Kinetic effects tube

Figure 14. Heat effect tube

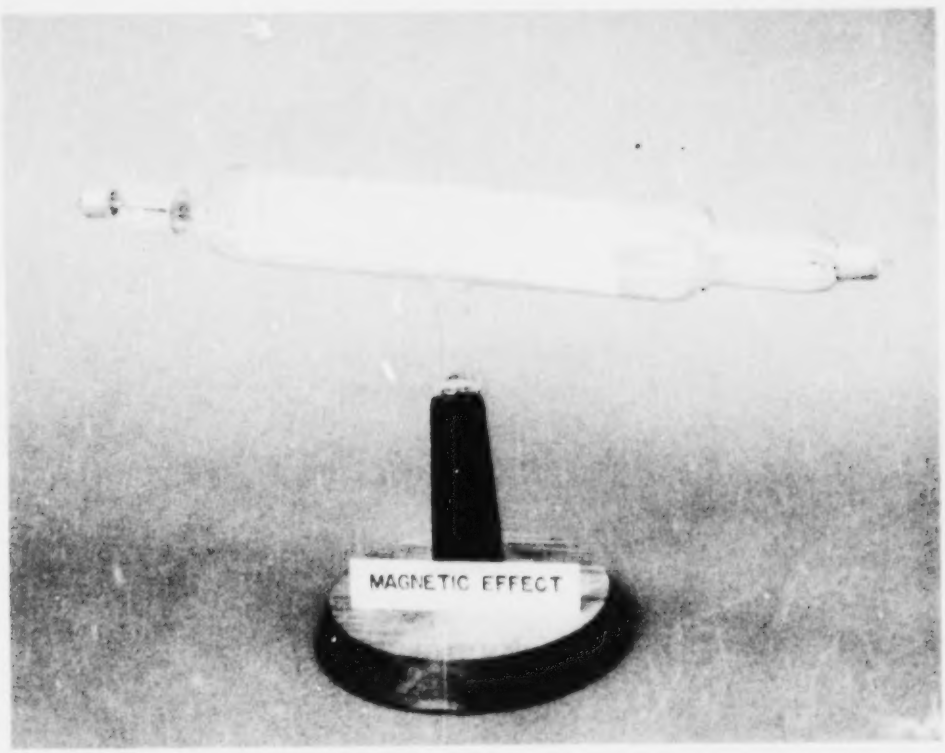

Figure 15. Magnetic effect tube

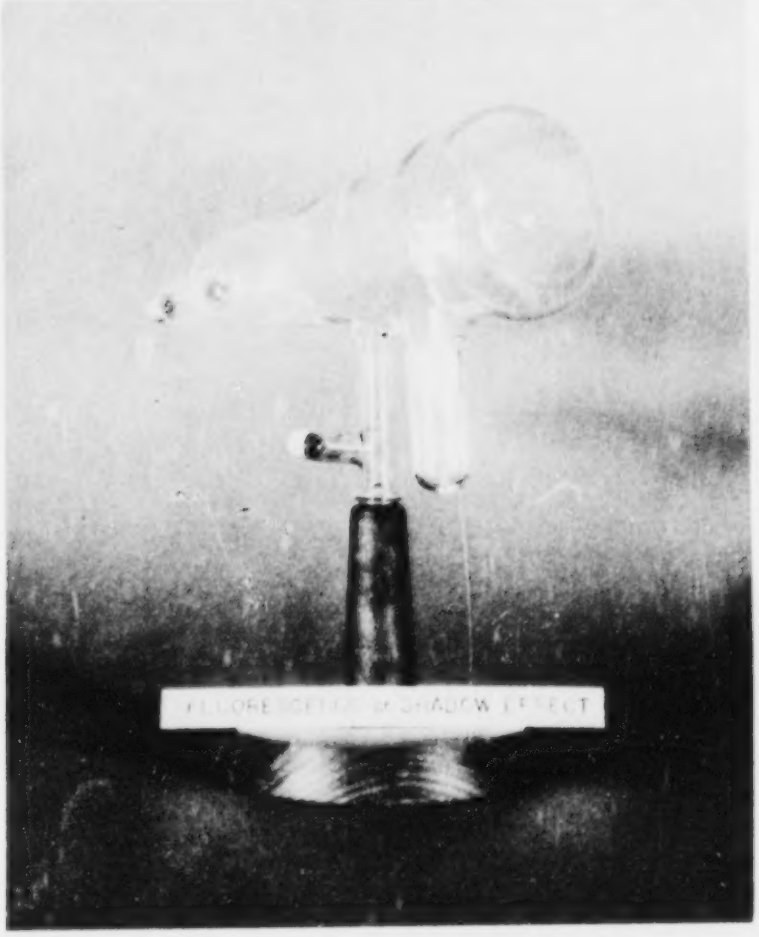

Figure 16. Fluorescence effect tube

A description of these three tubes and the results of laboratory observations follow.

2.3.2.1 Heat Effect Tube

The heat effect tube is used to demonstrate that cathode rays consist of rapidly moving electrons whose kinetic energy is converted to heat upon collision with an object. The tube consists of an evacuated glass bulb with a thin foil target positioned between opposed electrodes. The cathode has a concave surface to focus the electrons on a small spot of the foil. The focal spot on the foil can easily be heated to white heat and destroyed if one is not careful.

A new heat effect tube was tested using an induction coil capable of a 3-inch spark as the voltage source. When operated with the proper polarity, the tube ran at about 15 kV, as measured by a parallel spark gap, and the focal spot glowed a brilliant red but no X-rays were detected.

Upon reversing the polarity, the tube ran at about 55 kV and, as expected, showed no signs of operating as a heat effect tube. Instead, a faint blue discharge filled the tube and X-ray generation was observed. After a few minutes of operation with reverse potential, the tube was reconnected to operate under a forward potential. However, no change from the reverse potential characteristic was observed - the tube still operated at approximately 55 kV, produced X-rays, and did not show the heat effect. The operation under reverse potential had apparently caused the tube to evacuate due to an internal getter action. Initially it was possible to heat the tube, thereby outgassing internal parts, to restore it to its original operation for demonstrating the heat effect, but after continued use the tube's designed operating characteristic was permanently destroyed and it operated only as an X-ray tube.

Measurements of the X-ray output with both forward and reverse potential were made using thermoluminescent dosimeters placed along the radials shown in figures 17 to 19. Figures 17 and 18 show iso-exposure rate curves in the planes passing through the center of the target foil perpendicular to the axis of the tube, and perpendicular to the plane of the foil, respectively, with reverse potential applied to the tube. Figure 19 shows iso-exposure curves in the same plane as shown in figure 18 but with forward potential applied to the tube. The data of figure 19 were not converted to exposure rates because of inability to determine operating time due to intermittent and faulty operation of the tube. Although a direct comparison of exposure rates is not possible, figure 19 is presented to enable comparison of iso-exposure patterns for forward and reverse potential. Measurements made with a large induction coil (capable of 6-inch spark) showed an increase by a factor of six in the X-ray intensity and an increase in voltage to about 75 kV.

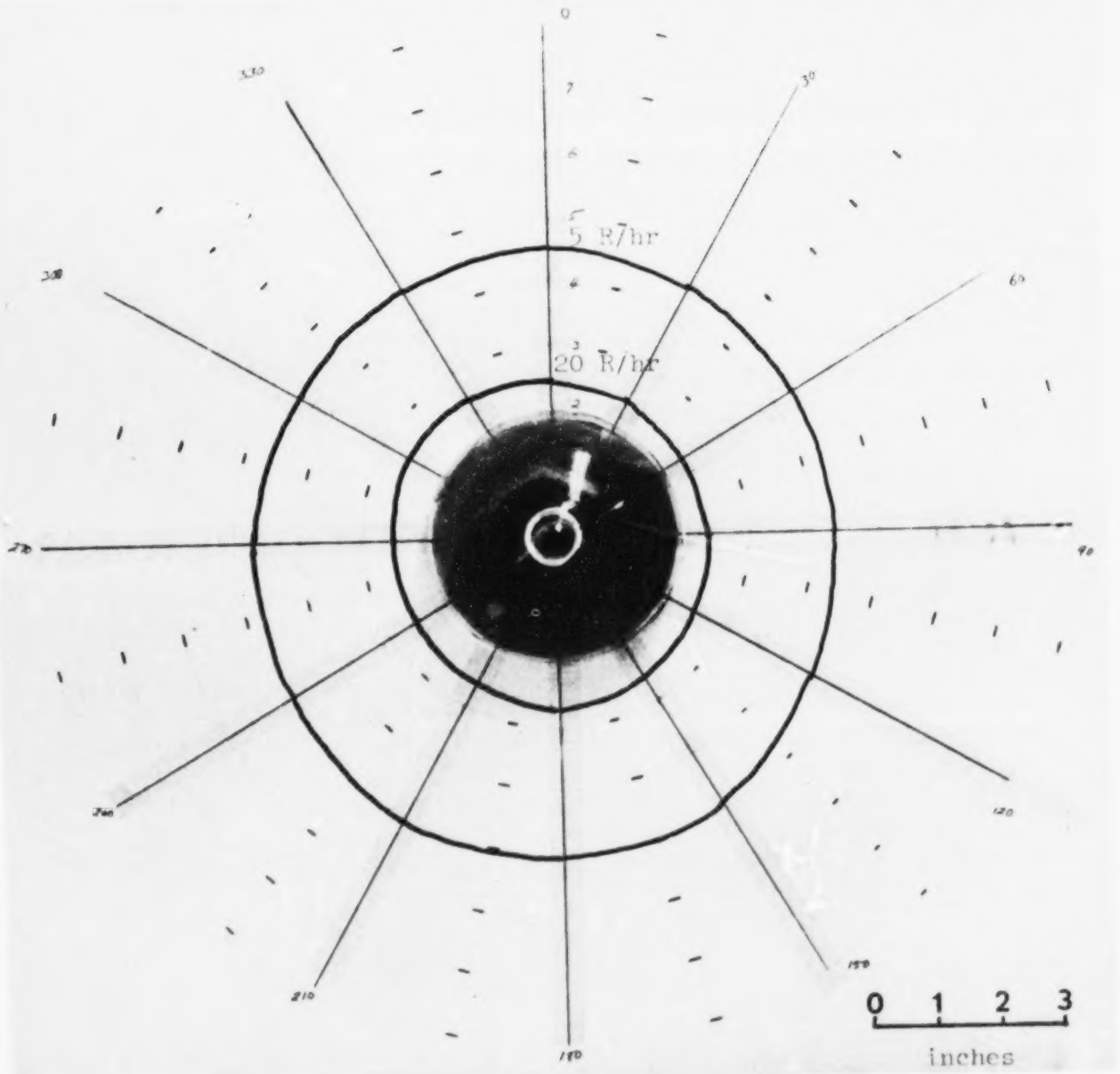

Figure 17. Iso-exposure rates for heat effect tube operating under reverse potential. Rates shown in plane perpendicular to tube axis and intercepting target foil.

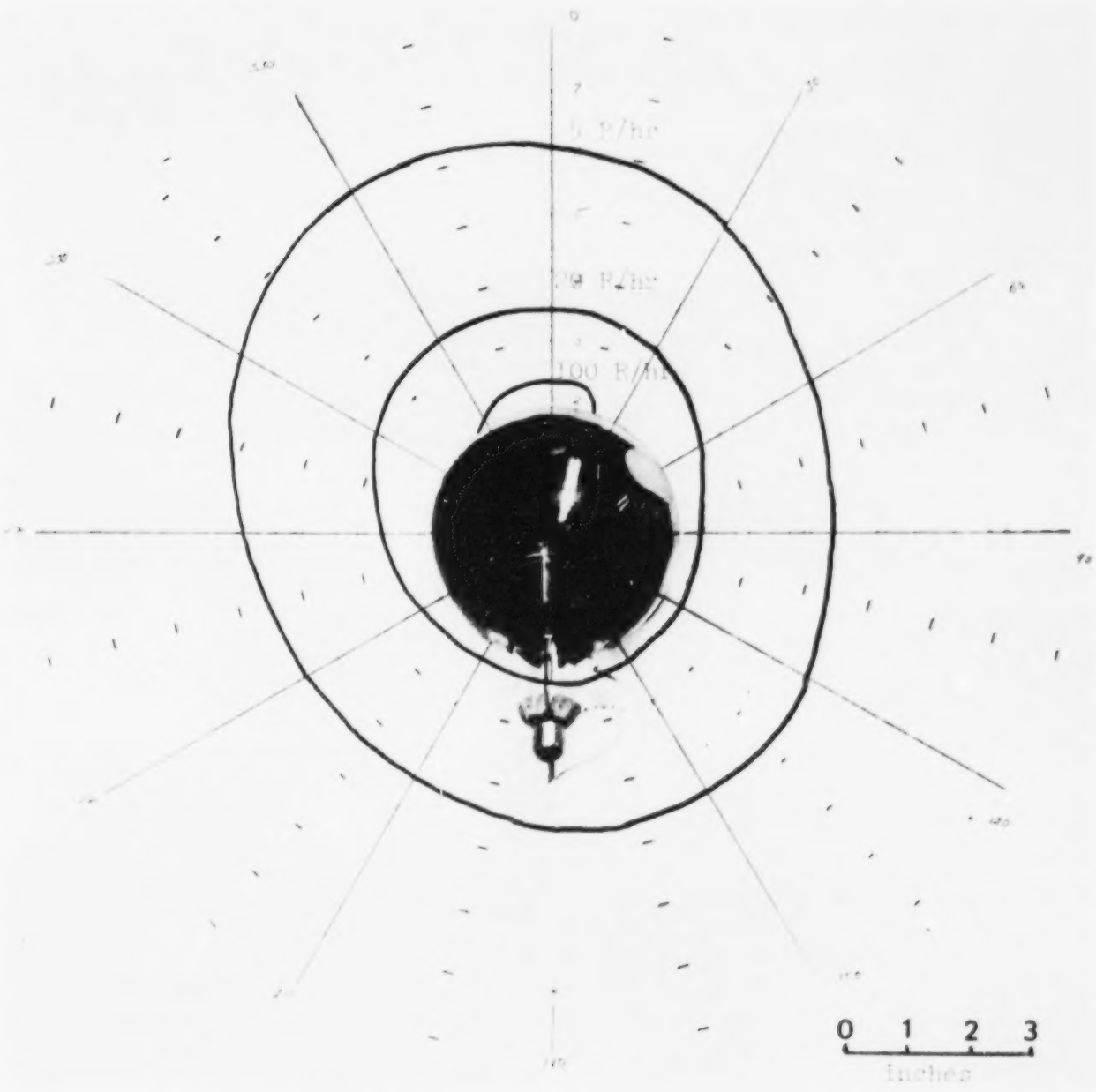

Figure 18. Iso-exposure rates for heat effect tube operating under reverse potential. Rates shown in plane perpendicular to target foil.

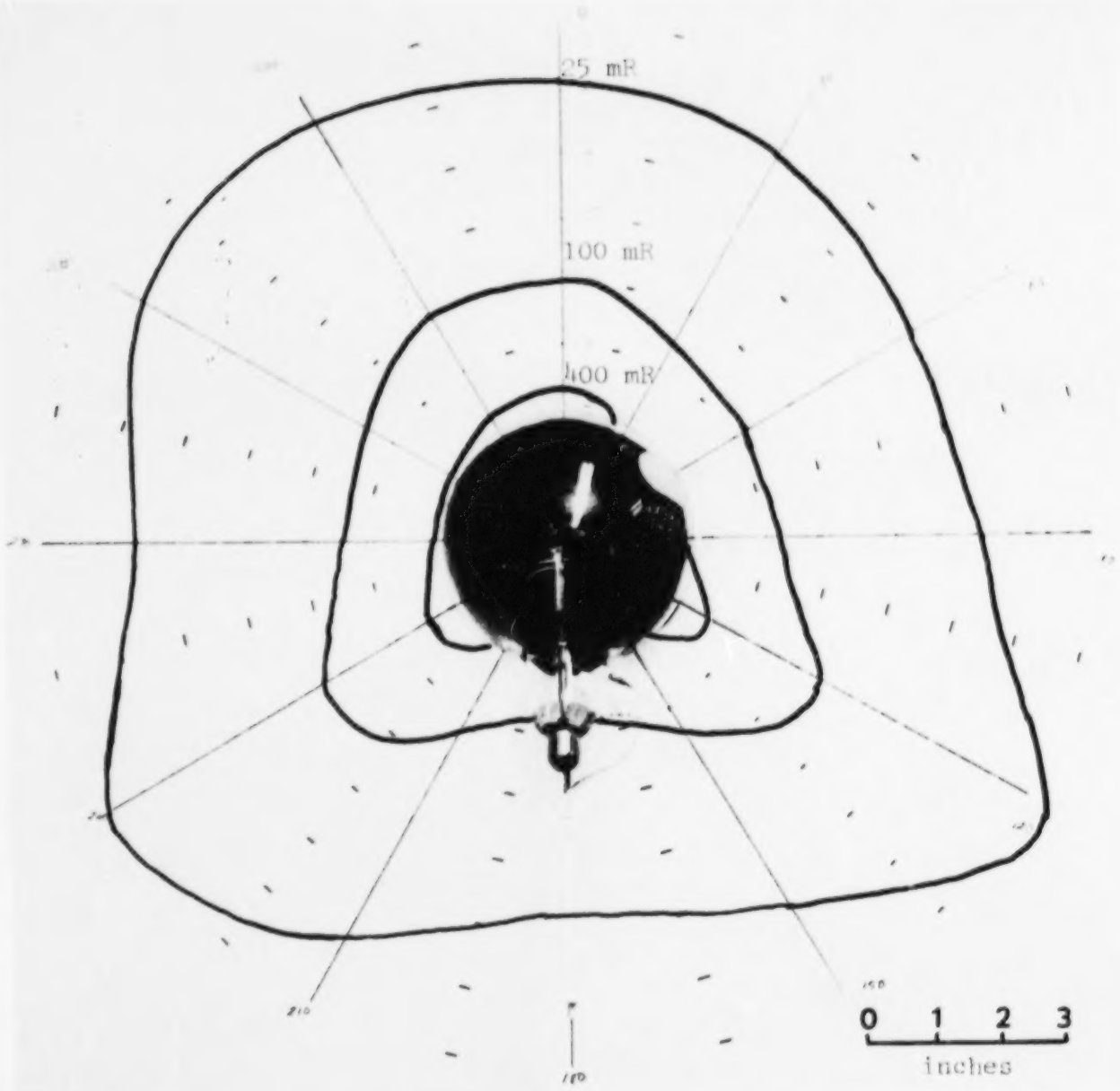

Figure 19. Iso-exposure levels for heat effect tube operating under forward potential. Data shown in plane perpendicular to target foil.

2.3.2.2 Magnetic Effect Tube

The magnetic, or deflection, effect tube demonstrates that cathode rays carry an electrical charge and can be deflected by a magnetic field. It consists of an evacuated glass cylinder with an electrode at each end. An aluminum strip, coated with fluorescent material, with a collimating slit at the cathode end is positioned between the electrodes. In a magnetic field the luminous line produced by electron bombardment of the fluorescent strip is deflected up or down according to the polarity of the magnet.

When the magnetic effect tube was used with the small induction coil (capable of 3-inch spark) it operated at 50 kV but dropped to approximately 15 kV within a few minutes. A CS-40A survey meter read approximately 1 R/hr initially at one foot from the front of the tube but dropped to less than 1 mR/hr, reflecting the lower operating voltage. Continued operation at that time showed no further production of X-rays. After a period of non-use for a few days the tube was retested and again produced X-rays for a short period (a few minutes). This recovery is apparently associated with an internal getter action within the tube which lowers the pressure enough to permit production of X-rays for a short period of time. No X-rays were observed when the reverse polarity was applied.

Iso-exposure curves are shown in figure 20, and represent the total exposure from the time the voltage was applied until the tube stopped producing X-rays. Since the output varied with time until X-ray production stopped, it was not possible to convert the data to exposure rates.

2.3.2.3 Fluorescence Effect Tube

The fluorescence, or shadow, effect tube demonstrates that cathode ray energy may be converted into visible radiations by fluorescence of the glass walls of the tube resulting from electron bombardment. A metallic object such as a Maltese cross is placed so that its shadow can be cast on the glass wall of the tube. From observation of this shadow it can be shown that the cathode rays producing this pattern travel in straight lines.

Three fluorescence effect tubes were tested in the laboratory but none operated correctly due to high pressure. A spot check was made in the field on a tube of this type that showed an exposure rate of 300 mR/hr. The measurement was made at a point about one foot from the tube on a line perpendicular to the tube axis through the center of the tube. This confirms the findings of Parsons (4), who reported X-ray production from this type of tube. He reported rates of 31 rem/hr at the face of the tube and 0.79 rem/hr at a distance of 25 cm from the face as measured with film.

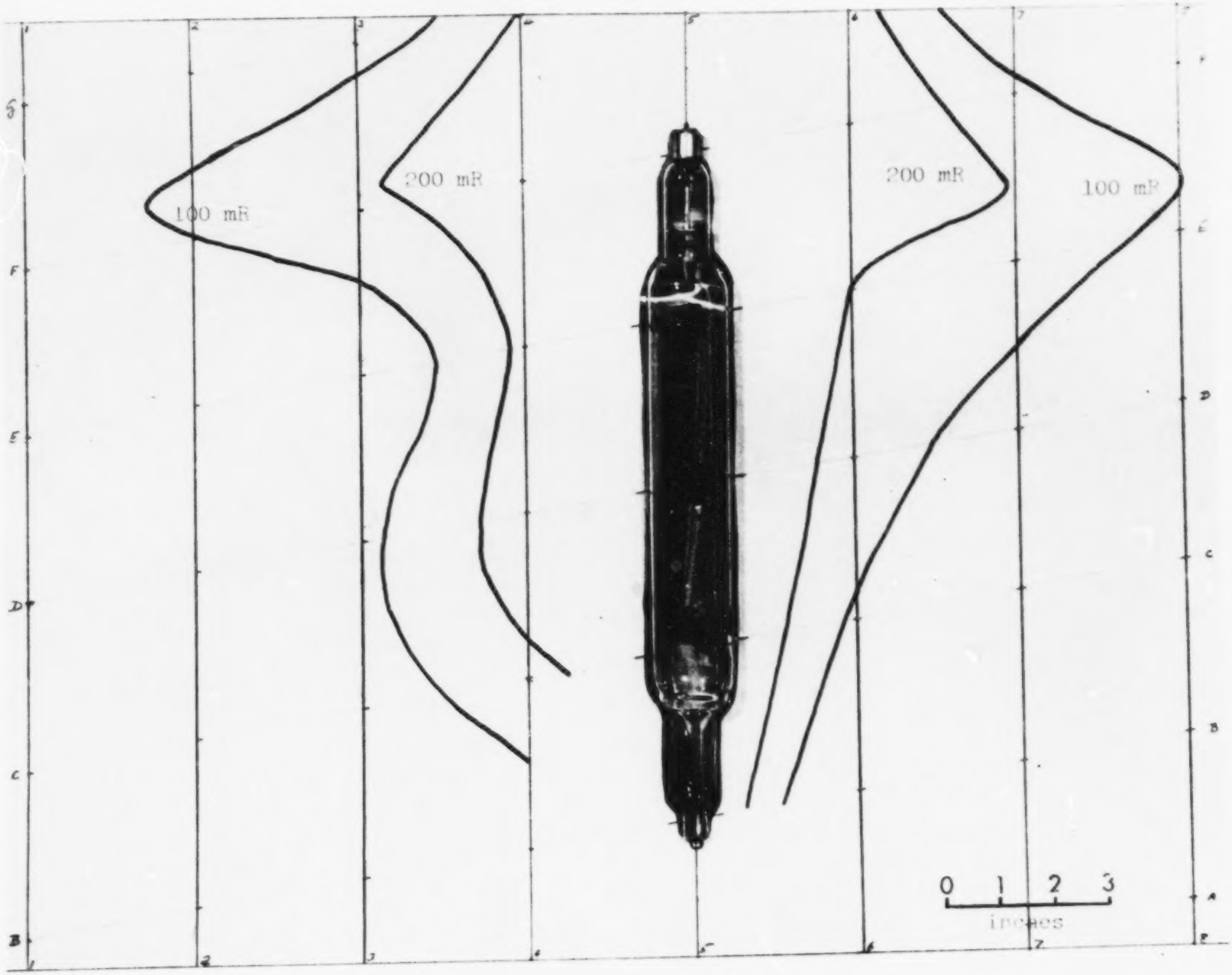

Figure 20. Iso-exposure levels from magnetic effect tube operating under forward potential

2.4 Discussion and Conclusions

2.4.1 Cold-Cathode Gas Discharge X-ray Tubes

From an analysis of the experimental data, the following conclusions can be made with regard to cold-cathode X-ray tubes:

a. The major output of the tube is in the hemisphere facing the front or surface of the target anode and is symmetrically distributed, except for the shadow of the cathode arm.

b. The output in the hemisphere behind the target anode is attenuated by a factor of up to several hundred by the anode and anode stem.

c. The output of the tube is strongly dependent on whether or not the tube polarity is correct and on the voltage and current capabilities of the power source.

d. The general condition of the tube is also significant, there being considerable variation from one tube to another of the same kind.

e. The radiation intensities observed at various distances are in general agreement with the inverse square law.

2.4.2 Cold-Cathode Gas Discharge Tubes (not intended to produce X-rays)

With respect to the gas discharge tubes which fail to produce X-rays, it is believed that excessive gas pressure was the predominant factor which prevented X-ray production. Electrons are accelerated by the electric field and quickly collide with gas atoms thus never gaining sufficient energy to produce X-rays. If pumps capable of producing a high vacuum were connected to the open tubes, or an internal getter action reduced pressure in the sealed devices, X-rays could be expected. To attain the degree of vacuum necessary for X-ray production, equipment such as an oil diffusion or vapor ejector pump would be required and, although a survey was not conducted, it is felt that this type of equipment is not generally available in high schools where a majority of these tubes are found.

With regard to X-ray production from gas discharge tubes, the following may be concluded:

a. X-ray output is sporadic. Under identical conditions of operation, it may vary from one tube to another and for the same tube from day to day. In addition, the rate of output may vary during a given period of operation.

b. Gas pressure within the tube is one of the controlling factors in X-ray production.

c. Tube construction plays an important part in the X-ray output obtainable from a tube. The efficiency of X-ray production is a function of the target material. In addition, the thickness and composition of tube walls will determine the exposure rates observed.

d. The output of the tube is strongly dependent on the voltage and current capabilities of the power source and the polarity of the voltage.

e. It is not possible to predict whether a tube will produce X-rays, how long it will produce X-rays, or in what quantity. Even in the case of identical tubes, one may be an X-ray producer and the other may not while both are operating properly in the manner for which they were designed. Therefore, proper operation cannot be used as a criterion for whether or not the tube may be producing X-rays.

Tube polarity was investigated as part of our laboratory observations since it is a simple matter to apply improper polarity to a tube when using Tesla coils and induction coils similar to those found in teaching institutions. As suspected, this one factor determines to a large extent the X-ray output. Improper polarity can result in damage to the tube, an increase in the production of X-rays, or both. It is important that this be understood by the user of these devices and that the determination of proper polarity not be accomplished through a procedure of elimination.

Since the X-ray production from gas discharge tubes is unpredictable, it is not possible to pinpoint those specific tubes which are X-ray producers and those which are not. Neither is it possible to predict in advance what the performance of a specific tube may be from day to day. It is only possible to generally state that X-ray production will exist where there is a source of electrons, a target, sufficiently high voltage and tube gas pressure within the proper range. Any of the demonstration tubes used in the XECL study could conceivably be operated under these conditions and consequently would be capable of producing X-rays. The quantity and energy of the radiation produced will depend upon the construction of the tube and its operating current and voltage. Therefore, whenever there is a choice, the tube should always be operated at its lowest current and its lowest voltage.

In conclusion, it should be stated that although these tests were made with many devices available from scientific supply houses, no claim is made that those studied in this report represent a complete listing. Tests with hot-cathode devices were conducted (see appendix C). By utilization of a hot cathode, operation at much lower voltages is possible. Tests with two tubes of this type show no X-ray production when operated as directed with a maximum potential of 5000 volts. Whenever possible, use of these hot-cathode devices is advised.

3. RECOMMENDATIONS REGARDING USE AND SALE OF GAS DISCHARGE DEVICES

Based on the data presented in this report, recommendations are set forth with regard to the use and sale of gas discharge devices. It is emphasized that these recommendations are based solely on limited laboratory observations and reflect the most severe cases encountered in these observations. No claim is made that by following these recommendations the exposure limits for students suggested by the NCRP in Handbook 32 will always be met. Instead, the recommendations are designed to provide a basis for sound radiological health practices under which general adherence to the recommended level can be achieved. These recommendations are given with individuals less than 18 years of age in mind and are addressed to the science teacher, the distributor and responsible public health agencies.

3.1 Recommendations to Educational Institutions

Instructors responsible for the use of radiation-producing devices should be familiar with NCRP Report No. 32, "Radiation Protection in Educational Institutions." They should be conversant with the biological effects and other matters related to radiation safety. This information should be passed on to the student as part of the teaching process related to the study of X-rays. Specific recommendations with regard to the use of these devices under special conditions are given below.

3.1.1 Unshielded Cold-Cathode Gas Discharge X-ray Tubes

The use of an unshielded cold-cathode X-ray tube in a classroom demonstration should never be considered acceptable.

3.1.2 Shielded Cold-Cathode Gas Discharge X-ray Tubes

Recommendations:

a. The maximum exposure rate at any point through the shielding should not exceed 10 mR per hour at a distance of 1 foot.

Note: This recommendation is based on an exposure distance of 1 foot from the tube and an operating time of 5 minutes. A safety factor of ten is applied to take into consideration viewing distances of less than 1 foot and operating times greater than 5 minutes.

b. The primary beam from the beam port shall álways be directed away from the class.

c. No student shall use this equipment without appropriate on-the-spot supervision by the teacher.

d. No experiment should result in exposure greater than 10 mR for any student 18 years of age or younger.

3.1.3 Gas Discharge Tubes Not Primarily Intended to Produce X-rays

As reported, certain tubes in this category produce X-rays incidental to their intended use. Although measurements indicate the output exposure levels from such tubes to be significantly less than would be expected from a cold-cathode X-ray tube (often by a factor of 100 or more), the potential for student exposure does exist. The educational benefit derived from these devices is gained by visual observation of their operation. The effects of external magnetic or electric fields are often of interest and require access to the tube while operating. To meet these requirements, unshielded operation of these devices may be required. The recommendations for use of tubes in the category suspected of producing X-rays are based on these considerations.

The recommendations are as follows:

a. Unshielded tubes should be used only for demonstrations conducted by the instructor. No student should operate an unshielded tube.

b. Tubes should always be operated at lowest current and voltage possible and time of operation kept to a minimum.

c. No student should stand closer than 8 feet from an unshielded tube when it is operating.

3.2 Recommendations to Distributors

3.2.1 No device designed for the purpose of producing X-rays shall be sold without adequate shielding (see 3.2.3 below). The only exception to this would be in the case where a letter from the local responsible radiological health agency vouches for the existence of adequate shielding at the installation which intends to make the purchase.

3.2.2 Tubes designed for the production of X-rays or those that have been shown to produce X-rays incidental to their intended use should be clearly labeled to the effect that they may emit X-rays when energized.

3.2.3 The shielding provided with X-ray tubes should limit the maximum exposure rate at any point with the exception of the beam port to 10 mR per hour at a distance of 1 foot. In keeping with the generally accepted philosophy of radiation protection, this level should be kept as low as possible.

3.2.4 The purchaser should be informed of NCRP Report #32 or provided a copy with each purchase.

3.2.5 The purchaser should be informed that equipment designed to produce X-rays may require registration with the appropriate State or local radiological health agency.

3.2.6 The appropriate radiological health agency should be notified of the sale of cold-cathode gas discharge X-ray tubes and other cold-cathode tubes that have been shown to produce X-rays.

3.3 Recommendations to State or Local Radiological Health Programs

3.3.1 The appropriate agency should register all devices designed for the production of X-rays.

3.3.2 Instruction and assistance in the recommended use and operation of gas discharge tubes should be offered to teachers using this equipment. This instruction should include radiation protection principles to eliminate or reduce radiation exposure to students.

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APPENDIX A

SPARK-GAP VOLTAGES

A recognized method for high voltage measurement utilizes spark gap distances. A tabulated listing of this type of information is shown in table A1 (6). When measuring the operating voltage of a gas discharge tube, the determination should be made with gaps connected in parallel with the operating tube. This procedure will take into account loading of the high voltage source.

Table A1. Spark-gap Voltages in Air (760 mm Hg, 25° C)

Peak voltage (kilovolts)	Length of spark gap (cm)				
	Spherical electrodes				Needle point electrodes
	2.5 cm diam.	5 cm diam.	10 cm diam.	25 cm diam.	
5	0.13	0.15	0.15	0.16	0.42
10	0.27	0.29	0.30	0.32	0.85
15	0.42	0.44	0.46	0.48	1.30
20	0.58	0.60	0.62	0.64	1.75
25	0.76	0.77	0.78	0.81	2.20
30	0.95	0.94	0.95	0.98	2.69
35	1.17	1.12	1.12	1.15	3.20
40	1.41	1.30	1.29	1.32	3.81
45	1.68	1.50	1.47	1.49	4.49
50	2.00	1.71	1.65	1.66	5.20
60	2.82	2.17	2.02	2.01	6.81
70	4.05	2.68	2.42	2.37	8.81
80	....	3.26	2.84	2.74	11.1
90	....	3.94	3.28	3.11	13.3
100	....	4.77	3.75	3.49	15.5
110	....	5.79	4.25	3.88	17.7
120	....	7.07	4.78	4.28	19.8
130	....	....	5.35	4.69	22.0
140	....	....	5.97	5.10	24.1
150	....	....	6.64	5.52	26.1
160	....	....	7.37	5.95	28.1
170	....	....	8.16	6.39	30.1
180	....	....	9.03	6.84	32.0
190	....	....	10.0	7.30	33.9
200	....	....	11.1	7.76	35.7
210	....	....	12.3	8.24	37.6
220	....	....	13.7	8.73	39.5
230	....	....	15.3	9.24	41.4
240	....	....	....	9.76	43.3
250	....	....	....	10.3	45.2
300	....	....	....	13.3	54.7

APPENDIX B

FIELD SURVEY INSTRUMENT CONSIDERATIONS

When making field survey measurements of the radiation output from gas discharge tubes, a number of factors must be considered in picking a suitable instrument. It is desirable to have both mR/hr ranges to measure low personnel exposure levels and R/hr ranges to measure the high exposure rates often observed near the discharge devices. A good low energy response is desirable since the tubes are generally operated at low voltages with little or no filtration. The problem of radio frequency (rf) interference must also be considered. High voltage sources, such as Tesla and induction coils, used to operate the tubes often produce sufficient rf energy to interfere with proper operation of an unshielded instrument.

Few commercial radiation survey instruments incorporating rf shielding exist. The Victoreen 440 RF is one example. The stability of this vibrating reed instrument is desirable but its maximum range of 300 mR/hr makes it difficult to measure high outputs associated with many of the tubes to be tested. In addition, an rf shielded instrument is much more costly than a similar instrument with no shielding. The wide range necessary can be met by most "Cutie Pie" type instruments. The Nucor CS-40A is felt to be a reasonable compromise between the need for a wide range instrument and the accuracy of readings obtainable from an instrument of this type. The relatively good low energy response of this instrument is also desirable for measurement of lightly filtered low energy X-rays.

The problem of rf interference can be solved for the non-shielded instrument by enclosing it within a shield. To construct a suitable rf reflective shield, the intrinsic impedance of the shield material should be significantly different from that of the impinging rf field. The material from which the shield is to be made must be able to be fabricated so that electrical continuity can be maintained at all seams. Since the instrument is to be placed within the shield, visibility of the dial and means by which dial adjustments can be made are additional requirements.

A fine mesh wire screen box is technically suitable but presents certain problems of operator access to instrument dials and is oft an additional bulky item to be carried. The use of an electrically conductive cloth was found to provide a useful substitute for the wire screen box. The technique has been used at the National Bureau of Standards for shielding survey instruments used around their linear accelerator.

APPENDIX B (cont'd.)

The material used for the shielding bag (fig. B1) was made from heavy marquisette,[1] an open mesh nylon screen material metalized with silver. Experience with this material shows that it can be fabricated with regular sewing practices without losing electrical continuity or causing leaks. The open weave allows adequate visualization of the instrument's dial. The bag as shown required one-half yard of material.

No determination of rf attenuation characteristics was made in our laboratory but Reynolds has reported on tests made on various metalized fabrics (7). He presents attenuation curves for a metalized heavy marquisette called "Attenutex" which show a minimum attenuation value of 40 dB over the frequency range 350 to 1000 MHz.

The bag shown in figure B1 was designed to be used with a Nucor CS-40A. A calibration curve for the CS-40A, with and without the rf shield, was obtained using the XECL free air chamber. Figure B2 is a plot of the correction factor (true R/hr to indicated R/hr) over the range of effective energies, 12-34 kV. A variation in the correction factor of 25 to 40 percent is shown over the energy range. The significant fact is that placement of the survey instrument in the rf shield only slightly changes the response when compared to that of an unshielded instrument. A maximum variation of 8 percent can be seen at the low energy points of the curve.

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[1]Heavy marquisette obtained from: Swift Textile Metalizing and Laminating Corporation, 10 Love Lane, Hartford, Connecticut.

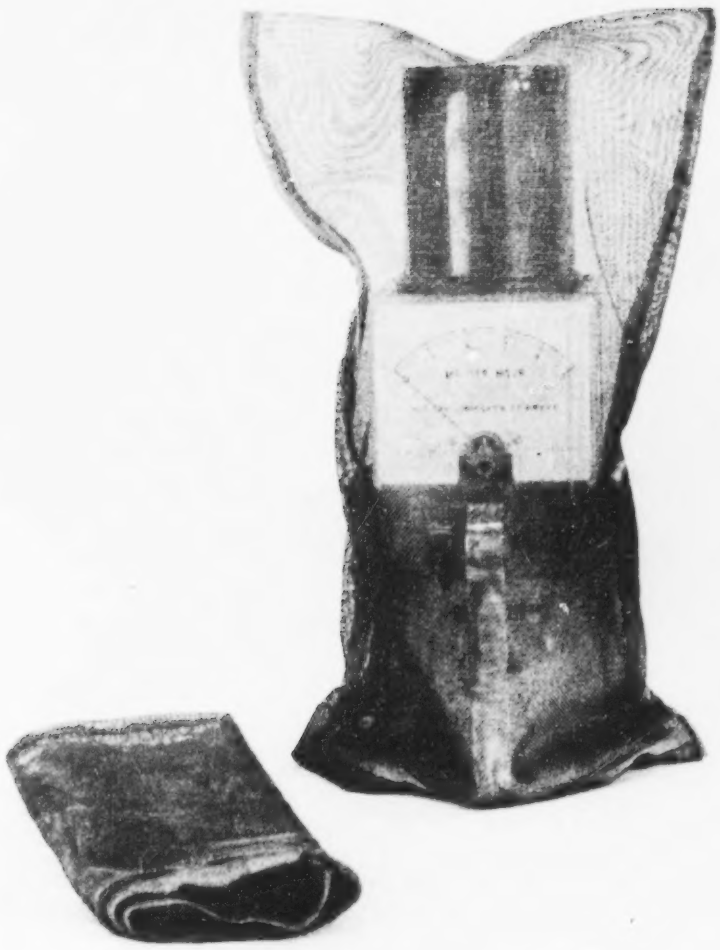

Figure B1. CS-40A radiation survey instrument enclosed in an rf shield. (Note second folded bag in foreground.)

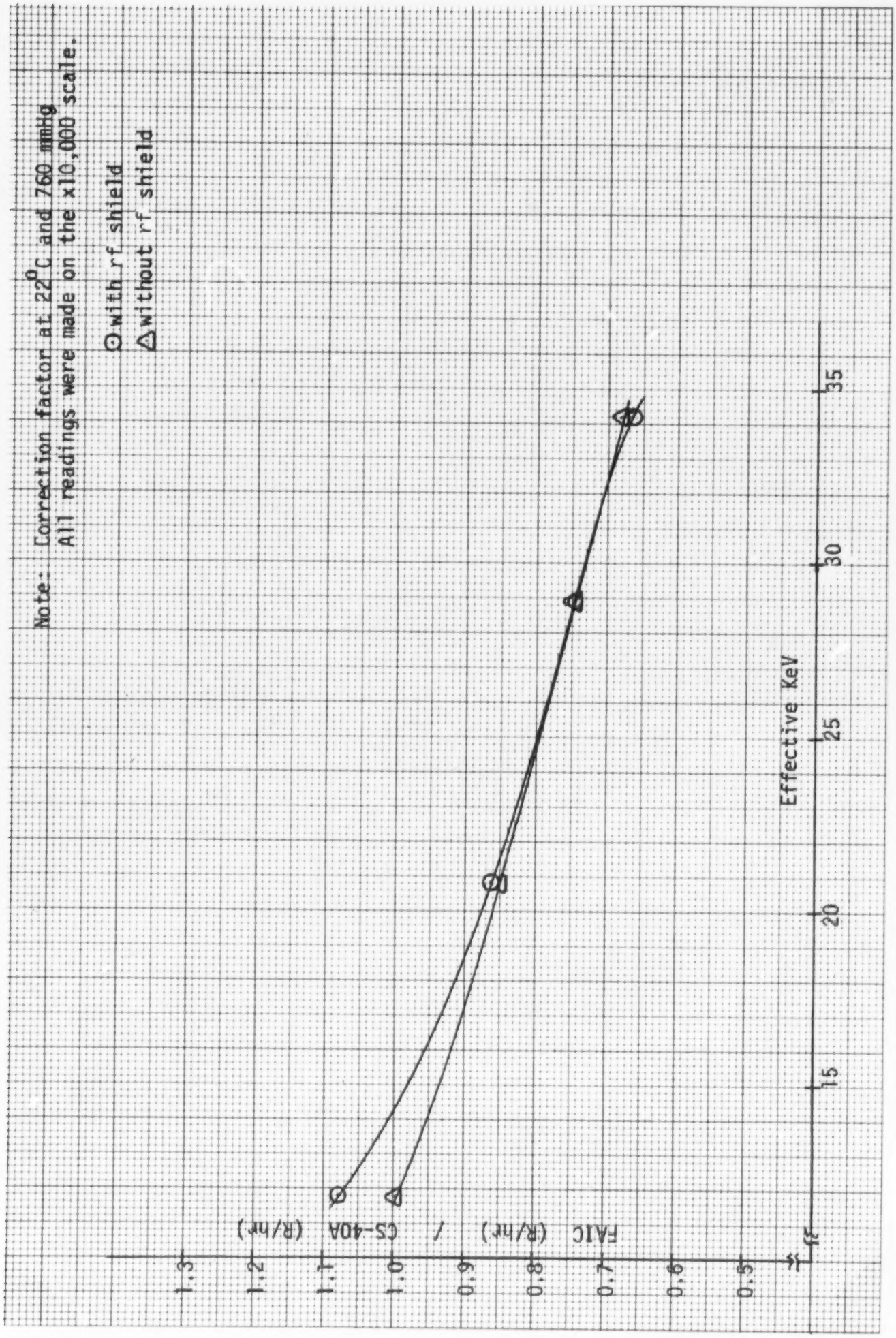

Figure B2. Typical CS-40A energy dependence curve with and without rf shield

APPENDIX C

HOT-CATHODE DEMONSTRATION TUBES

At least one manufacturer[1] has introduced several hot-cathode tubes designed to demonstrate the properties of cathode rays without the accompanying X-radiation that has been observed with cold-cathode gas discharge tubes. By utilizing a heated filament to provide a source of electrons, operating voltages significantly less than that required for a cold-cathode gas discharge tube can be achieved. A Perrin tube, figure C1, and a fluorescent effect, or maltese cross, tube C2, were tested for possible emission of X-ray radiation.

The instructions supplied with the tubes specify a maximum filament voltage of 7.5 V and an anode voltage of 2000-5000 Vdc with 4000 Vdc being a typical operating level. The tubes were operated from a Sorensen model 9030-5 d-c high voltage supply. This unit, rated at 30 kVdc, was operated over the specified voltage range by varying input voltage. It was found that 2000 volts was the minimum voltage necessary to assure reliable operation of the tubes. For the two tubes tested, 3500 to 4000 volts appeared to be the most desirable operating range to carry out the experiments suggested by the manufacturer.

The tubes were also operated at voltage levels in excess of the specified maximum value to determine the possibility of X-ray production. They were surveyed with a CS-40A portable survey meter while operating at voltages up to 10,000 volts. No radiation was detected from the Perrin tube, and the fluorescence effect tube showed no X-ray production below 8000 volts, which is well above the manufacturer's specified operating range. An attempt was made to operate the tubes with an induction coil using a small spark gap to limit the maximum voltage. Operation using this type of high voltage source was found to be unsatisfactory.

In addition to the two tubes tested, a demonstration diode, a demonstration triode and a deflection effect tube are known to be available in this line of devices. Although tests were made with only two tubes, it would be expected that these other hot-cathode tubes would not produce X-rays when operated within their specified voltage range.

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[1] Teltron Limited, 32/36 Telford Way, London W3, England.

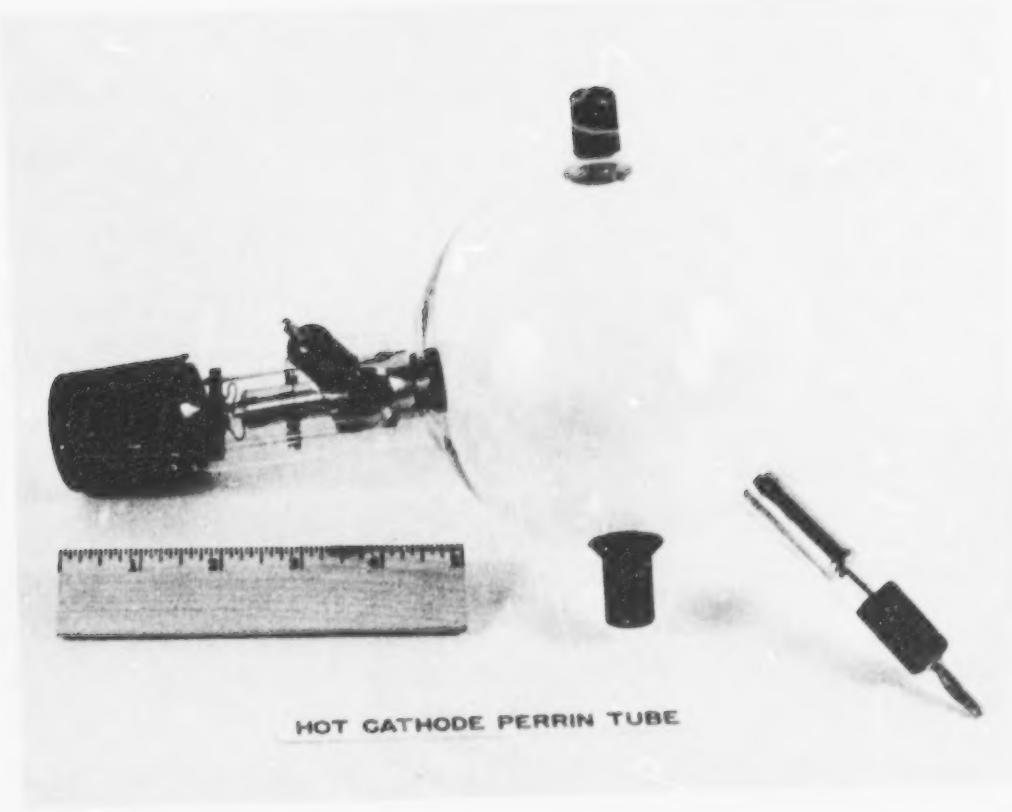

Figure C1. Hot-cathode Perrin tube

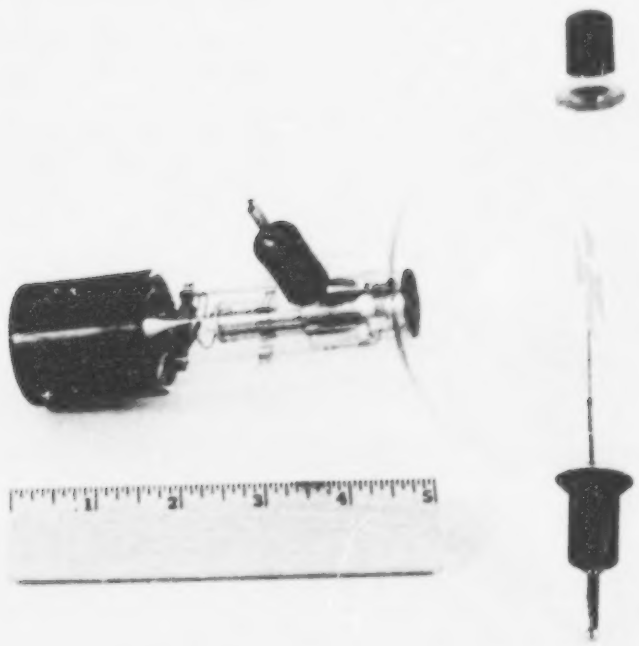

Figure C2. Hot-cathode fluorescence effect tube

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X-RAY EMISSION FROM COLD-CATHODE GAS DISCHARGE TUBES USED FOR EDUCATIONAL PURPOSES - William S. Properzio, Ray C. Woodcock, and Sidney D. Heidersdorf; February 1970; BRH/DEP 70-1; DEP, BRH, EHS, PHS, DHEW.

Accession No.

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(over)

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KEY WORDS:
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Cold-cathode X-ray tube
X-ray tube